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LAND USE IN LCA

Life cycle inventory modelling of land use induced by crop consumption

Part 2: Example of wheat consumption in Brazil, China, Denmark and the USA

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Abstract
Background, aims and scope Most life cycle inventory data for crops do not include the ultimate (marginal) land use induced by crop consumption. The aims of this study were to present, document and discuss a method which can solve this problem and, furthermore, to present concrete examples for wheat consumption in Brazil, China, Denmark and the USA. A global scope is applied and the simulated adaptation to increased wheat demand corresponds to a long-term temporal scope under present market conditions with present technology.
Materials and methods The economic general equilibrium model, Global Trade Analysis Project (GTAP) is modified and applied. Agricultural statistics and a number of global land use and land cover datasets are used in the modification and the processing of the model output. Some of the land use datasets are processed by use of a geographic information system tool.
Results The net expansion of the global agricultural area per tonne of wheat consumed in Brazil, China, Denmark and the USA is estimated at 2,000, 260, 1,700, and 3,200 m^2, respectively. For Brazil, the expansion mainly affects tropical evergreen forest. For China and the USA, the expansion mainly affects boreal deciduous forest, savanna, open shrubland and tropical evergreen forest, and for Denmark, it mainly affects savanna, tropical evergreen forest and dense shrubland. The areas affected are quantified in the land use life cycle inventory (LCI) produced for the four countries.
Discussion The method applied allows for an even more detailed land use LCI than the one presented in this study. Results are influenced by existing global trade patterns and their inertia. Such aspects should be acknowledged in life cycle assessment (LCA). The method takes its starting point in consumption rather than production.
Conclusions The method presented makes it possible to simulate the main mechanisms of the global agricultural system and thereby construct an LCI containing the land use induced by crop consumption in a given region and the nature types (biomes) affected. The results are sensitive to changes in the so-called Armington elasticities representing the inertia of global trade patterns. It is considered reasonable to double the standard elasticities in the GTAP model for the construction of LCI data. Wheat consumption in different countries result in different land use consequences due to differences in trade patterns, which are governed by transport and trade costs, among other factors.
Recommendations and perspectives The modelling could be improved by incorporating a mechanism simulating

Preamble The present paper is the second in a series of two. Based on the conceptual aspects outlined in the first paper (Kløverpris et al. 2008), this second paper presents a method for LCI modelling of crop-related land use, which is tested and discussed.

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legal fertiliser and pesticide restrictions, by better assessment of the amount of land suitable for livestock but not crop production (grazable land), by including irrigation and by a further differentiation of land fertility. Moreover, the method could be expanded to include intensification aspects in the LCI. The method could inspire a new approach to general LCI modelling in LCA and may also be of interest in the debate on the environmental impacts of biofuels.

Keywords Agriculture · Consequential LCA · GTAP (Global Trade Analysis Project) · Indirect land use change · LCI · Marginal production

1 Introduction

The production of crops is dependent on land, which is a constrained resource in several regions of the world. Increased demand for one crop may therefore lead to displacement of another crop, which may be compensated for by production elsewhere. This presents a challenge when assessing land use impacts in life cycle assessment (LCA) because it complicates the identification of the areas ultimately affected by crop consumption (Kløverpris et al. 2008). Schmidt (2008) develops several scenarios for the identification of ultimate land use caused by wheat consumption in Denmark. In one scenario, barley is applied as the crop displaced by Danish wheat (with reference to Weidema 2003), and Canada is identified as the marginal supplier of barley, i.e. the country compensating for the reduced supply of Danish barley. Canada is pointed out because it is predicted to have the largest gross increase in the production of barley up to 2016 (FAPRI 2006). This approach is a major step forward compared to previous land use assessment in LCA, which has only focused on the direct crop supplier (e.g. Nielsen et al. 2003). However, the identification of the marginal supplier suffers from some weaknesses. For instance, one of the main reasons that Canada has the largest increase in barley production is that it already has the fourth largest area of barley harvested in the world (FAOSTAT 2007). If Canada were subdivided for modelling into smaller units without any changes in agricultural production, the country would no longer be identified as the marginal supplier with the procedure applied. As the identification of marginal suppliers should not depend on the size of countries, there is a need for further improvement of the methodology. This should allow for the possibility that more than one crop in one country is affected by changes in crop demand, which is also acknowledged by Schmidt (2008). Furthermore, transport and trade costs should be taken into account (Kløverpris et al. 2008).

The purpose of the present paper is twofold. Firstly, to present, document and discuss a method for establishing life cycle inventories for land use induced by crop consumption and, secondly, to illustrate the use of the method with concrete examples for consumption of wheat in four countries, each with their own distinct characteristics, namely Brazil, China, Denmark and the USA.

1.1 Scope

Agricultural goods are subject to international trade, and consequently, the geographical scope is global. The study focuses on long-term production and land use changes induced by wheat consumption under present market conditions and with present agricultural technology. The methodological scope comprises consequential LCA and neoclassical economic modelling. The purpose of consequential LCA is to assess the actual consequences of a change, in this case the land use consequences of a decision to use crops in the life cycle of a given product or service.

2 Methodology

The methodology applied in the present study is based on that proposed by Kløverpris et al. (2008). The standard version of the economic model Global Trade Analysis Project (GTAP) is modified and used to predict global land use changes caused by increased wheat demand in the four countries considered. The model is linked with a database, which is also modified slightly. The output from the model consists of relative changes in a number of variables, including agricultural production and land use. These are converted into physical units by use of agricultural statistics. The nature types (biomes) affected by agricultural expansion are determined from land cover maps and FAOSTAT data. The modification of the standard GTAP model is described in detail by Baltzer and Kløverpris (2008). Essentials of the GTAP model in the present context and the stepwise conversion procedure from GTAP outputs to quantification of affected biomes are specified below.

2.1 Modification of the standard GTAP model and database

The GTAP model is a general equilibrium model of the global economy focusing on international trade. The model is based on neoclassical economic theory in which prices adjust to create equilibrium between supply and demand of all goods, services and factors of production in the economy. The accompanying database (version 6) characterises the global economy in 2001 as the initial market equilibrium.

Suppose the initial market equilibrium is disturbed by a sudden increase in demand for wheat. To restore equilibrium, the price of wheat increases, thereby lowering demand and inducing farmers to grow more wheat. The increase in wheat supply can be brought about through three different channels (as discussed in Kløverpris et al. 2008): by converting unused land to agriculture to accommodate the expansion in wheat plantings (increasing demand for land); by intensifying cultivation (raising demand for non-land inputs); or by displacing other crops (lowering supply of non-wheat crops). Each of these channels have implications for other markets, be it land markets, markets for agricultural inputs (such as fertilisers) or markets for substitutable crops.

Thus, the initial shock spreads throughout the economy like ripples on a pond. The general equilibrium model is designed to track all these disturbances throughout the whole economy (as opposed to a partial equilibrium model that only looks at one or few markets in isolation). Also, the global scope of GTAP enables us to track the adjustments across borders through the international trade in goods and services, allowing for the possibility that, e.g. increased wheat demand in Denmark leads to expansions in the agricultural area in Brazil.

The results are determined by the interplay between the model itself (documented in Hertel 1997), the database and a set of behavioural parameters (documented in Dimaranan 2006). We use the standard version of these, modified by the features summarised below (and documented in greater details in Baltzer and Kløverpris 2008).

The standard GTAP database (version 6) contains 87 regions, which are aggregated to 22 in the modified version as this is considered adequate in the present context (Table 1). Each region in the standard model has 57 sectors. Those of main interest in terms of land use are the eight crop sectors and the four livestock sectors.[1] The rest is aggregated to three sectors, resulting in a total of 15 (Table 2).

All eight crop sectors (left column in Table 2) as well as two of the livestock sectors (ctl and rmk) need land for production. The two remaining livestock sectors (wol and oap) do not use land because wool mainly comes from sheep already accounted for in the cattle sector (ctl), and animal products not elsewhere classified (oap) typically come from livestock kept at farms, e.g. pigs and poultry.

[1] In the applied version of the GTAP model, forestry does not use land and is included in the manufacturing sector (mnf). This is simply an artefact of the standard GTAP model, and the study could be improved by incorporating a mechanism in the model that allows land to shift between managed forest and agriculture. Meanwhile, this interplay is partly captured outside the model in the present study because modelled agricultural land expansion can take place at the expense of forest, managed or unmanaged. See Section 2.4.

Table 1 Codes (abbreviations) for the 22 GTAP regions in the present study

Code	Region
aus	Australia
xoc	Rest of Oceania
chn	China
xea	Rest of East and South East Asia
jpn	Japan
xsa	Rest of S Asia
ind	India
can	Canada
usa	USA
mex	Mexico
xca	Rest of Central America
per	Peru
bra	Brazil
xla	Rest of South America
dnk	Denmark
xeu15	EU15 except Denmark
eu12	EU12 (new members)
xer	Rest of Europe
xsu	Rest of Former Soviet Union
xme	Middle East and North Africa
xsc	South African Customs Union
xss	Rest of Sub-Saharan Africa

In the standard model, the total amount of land is fixed, and consequently, simulation of agricultural expansion is not possible. Land supply curves (van Meijl et al. 2006) are therefore incorporated in the GTAP model. Via the following general formula, the land supply curve determines the relationship between land price (P) and the area of land being utilised in the relevant region (the land supply, A_u):[2]

$$P = b/(A_a - A_u) \quad (1)$$

where $b > 0$ is a region-specific coefficient determining the shape of the curve and $A_a > 0$ is the maximum amount of land available in the relevant region.

The general shape of a land supply curve is shown in Fig. 1. At lower degrees of land utilisation in a given region, the land price will be relatively unaffected by changes in land use (the flat part of the curve). At high degrees of land utilisation, the land price will be very sensitive to changes in land use (the steep part of the

[2] Baltzer and Kløverpris (2008) use standard GTAP notation: PM for land price (P), QO for land supply (A_u) and a for the maximum amount of land available (A_a), in accordance with van Meijl et al. (2006).

Table 2 Codes (abbreviations) for the 15 GTAP sectors in the present study

Code	Crop sectors	Code	Other sectors
pdr	Paddy rice	ctl	Bovine cattle, sheep and goats, horses
wht	Wheat	oap	Animal products nec
gro	Cereal grains nec	rmk	Raw milk
v_f	Vegetables, fruit, nuts	wol	Wool
osd	Oil seeds	food	Food processing
c_b	Sugar cane, sugar beet	mnf	Manufacturing
pfb	Plant-based fibres	svc	Services
ocr	Crops nec		

nec not elsewhere classified

curve). Consequently, agricultural expansion is less likely in regions with a high degree of land utilisation.

To better account for differences in land quality, the single land type used in the standard GTAP model is replaced by two land types in the modified version: *cultivable land* with potential for rain fed cropland and pastures and *grazable land* with potential for rain fed pastures only. The eight crop sectors (see Table 2) can only use cultivable land, whereas the land-dependent livestock sectors (ctl and rmk) can use both cultivable and grazable land.

Land supply curves for each land type in each region are implemented in the modified version of the GTAP model. The area of cultivable land available for agriculture (A_a in Eq. 1 for cultivable land) is estimated for each region by a general procedure subtracting steep areas, protected areas and human settlements from the total area of cultivable land estimated by Ramankutty et al. (2002) on the basis of climate and soil constraints. The area of grazable land available for agriculture (A_a in Eq. 1 for grazable land) is estimated for each region by a general procedure subtracting steep and protected areas, human settlements, deserts and cultivable land from the total land area (Fig. 2) implicitly assuming that arid, semi-arid and dry sub-humid areas can be used as pastures. The areas of cultivable land and grazable land utilised in each region (A_u in Eq. 1) are determined by overlaying a global map of cultivable land (Ramankutty et al. 2002) and a global map of cropland and pastures (Ramankutty et al. 2007). Coefficient b (see Eq. 1) is calculated via the following formula (for both land types):

$$b = V_u \times (1 - u)/u \qquad (2)$$

where V_u is the monetary value of land utilised in the relevant region (available in the GTAP database, Dimaranan 2006) and u is the regional utilisation of the relevant land type defined as A_u/A_a.

The so-called Armington elasticities (see Kløverpris et al. 2008) in the standard GTAP database are doubled. Besides representing the heterogeneity of products from the same sectors in different regions, the Armington elasticities capture a number of factors causing inertia in international trade patterns. Much evidence suggests that this inertia is stronger in the short term compared to the long term. This can be explained by long-running contracts or high transaction costs preventing buyers from shifting to a cheaper supplier in response to short-term price variations. The more time the market has to adjust, the more freely buyers will choose between domestic and foreign suppliers. Therefore, the Armington elasticities tend to increase with the time perspective (McDaniel and Balistreri 2002). The

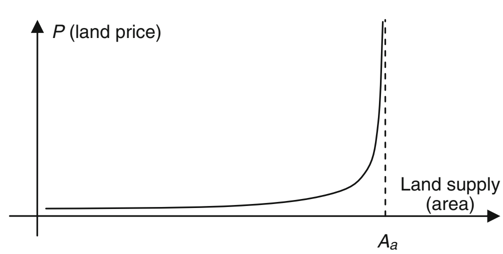

Fig. 1 Land supply curve (adjusted from van Meijl et al. 2006): General relationship between the area of land being utilised (land supply) and the land price. A_a indicates the maximum amount of land available in the region. Equation 1 describes the formula for the curve

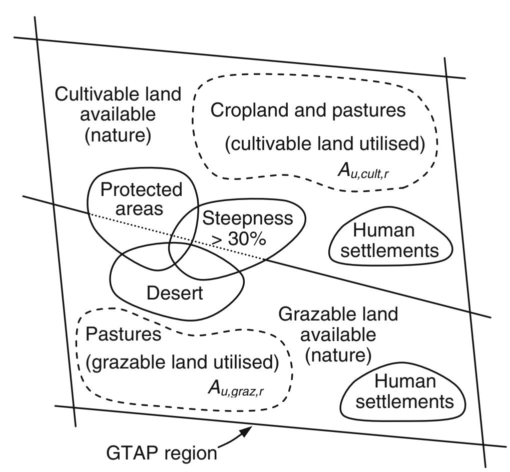

Fig. 2 Conceptual illustration of the regional land uses in the modified GTAP model. Steep and protected areas, human settlements and deserts are not considered available for agricultural production

doubling of the standard Armington elasticities is performed to reflect the long-term perspective usually applied in LCA.

The effect of crop demand on technological development and hence intensification (Kløverpris et al. 2008) is ignored in the core scenarios of this study, but investigated in the sensitivity analyses. The intensification observed in the core scenarios is therefore merely a result of optimised inputs to crop production driven by changes in crop prices. The effects of legal fertiliser and pesticide restrictions (Kløverpris et al. 2008) are not incorporated in the modelling as it has not been possible to establish a global overview of such restrictions.

The GTAP database is modified to better reflect the current world market conditions, e.g. the EU enlargement (from 15 to 27 member states) and China's entry into the WTO (end of 2001).

2.2 Simulation of increased demand for wheat in the GTAP model

The demand for wheat is increased by 500,000 tonnes in the four countries considered. This change is large enough to appear in the output from the GTAP model but small enough to be applicable in LCA, which typically concerns marginal changes compared to the total market (Weidema et al. 1999). The change in demand is constructed in the GTAP model by increasing the household preferences for wheat in the country of interest. The change is implemented in the households because these are end users in society. Establishing increased wheat demand elsewhere (e.g. in the industrial sectors) would create distortions in competitiveness and other effects that are not of interest in the present context. Due to the budget constraint of the households, the increase in wheat demand is balanced by an equivalent and equal decrease (the same relative change) in the household demand for other commodities. This is to make the change in demand as neutral as possible and thereby the results as generally applicable as possible.

2.3 Conversion of the output from the GTAP model

The output from the GTAP model expresses (among other things) the *relative* (percentage) changes in land use and crop production caused by the simulated increase in wheat demand. In order to convert the GTAP output to tonnes of agricultural production and area of agricultural land, it is combined with agricultural statistics (obtained from FAOSTAT 2007 and the overlay described in Section 2.1) in a set of equations, which are available in Electronic supplementary materials (ESM).

Although the expansion of the agricultural area is the main focus of this study, the underlying changes in crop production are also examined to see how they comply with the conceptual analysis presented in the first paper of this series. Thus, Eqs. 3–7 in ESM decomposes the total change in crop production into a part created by land expansion and another part derived from intensification. The crop sectors' change in production from a change in area is estimated (Eq. 6 in ESM) based on the initial distribution of cultivable land (Eq. 3 in ESM), the predicted changes in crop sector land use (Eq. 4 in ESM) and the initial crop yields (Eq. 5 in ESM). The crop sectors' change in production from a change in intensity is residually estimated by subtracting the area-related change in production from the total change in production (Eq. 7 in ESM).

Changes in crop yields are estimated based on production changes from intensification and the new land areas in the crop sectors (Eq. 8 in ESM), whilst the net expansion on cultivable land (both from cropland and pastures) is estimated based on output from the GTAP model (Eq. 9 in ESM).

For the country in which the wheat demand is increased (the scenario country), increased wheat production from change in area is further decomposed into expansion of agricultural area (Eq. 10 in ESM) and displacement of, respectively, other crops (Eq. 11 in ESM) and livestock (Eq. 12 in ESM). This breakdown is only possible for the regions in which the wheat sector is the only sector gaining land from other sectors and nature. This is the case for the scenario country in all scenarios and also for Canada in the US scenarios (due to Canada's close trade relations to the USA).

The net expansion on grazable land (from changes in pasture areas) is estimated from the initial grazable land use (overlay data) and GTAP output (Eq. 13 in ESM), whilst production changes in the livestock sectors are estimated from GTAP output and FAOSTAT production data (Eq. 14 in ESM).

2.4 Biomes affected by net expansion

After quantification of the net expansion caused by wheat consumption, the biomes expected to be affected are identified. Biomes are defined by potential natural vegetation, i.e. the "vegetation that would most likely exist in the absence of human activities" (Ramankutty and Foley 1999).

The net expansion predicted by the GTAP model is divided into two types. In a region with an increasing agricultural area, the predicted expansion is interpreted as transformation of an area that would otherwise have been transformed one season later (accelerated transformation). In a region with a decreasing agricultural area, the predicted expansion is interpreted as utilisation of agricultural land that would otherwise have been released one season earlier (delayed relaxation). In this study, one constant land quality (x) is assumed for agricultural land (cropland and pastures).

On the assumption that land released from agriculture returns to its original, natural quality (y) at a constant speed, the framework for land use life cycle impact assessment (LCIA) developed by Milá i Canals et al. (2007) shows that the impact of the two types of expansion is the same as long as the occupation period (from t_1 to t_2) is the same (Fig. 3). As all data in the GTAP model is given per year, the occupation period for all areas transformed is the same. If two areas of the same biome are affected by different types of expansion, these areas are therefore added up in the present paper. The background data, however, allow for a disaggregation of the two types of expansion. Note that because either type of expansion occurs on areas already about to change, the long-known problem of allocating initial transformation impacts to subsequent land use activities (see, e.g. Lindeijer et al. 2002) is eliminated.

To determine the biomes affected by expansion in a GTAP region, the likely geographical location of expansion *within* the region is first identified. This is done by first analysing the trend in utilisation of the two land types, cultivable and grazable land. The trend analysis is based on data for cropland and pasture areas (FAOSTAT 2007) and data on the relative land type utilisation.[3] Thereafter, the trends in croplands and pastures are used as indicators of where in the region the expansion predicted by the GTAP model occurs. Data on these trends consists of agricultural statistics (FAOSTAT 2007) and cropland maps from 1970 and 1990 (Ramankutty and Foley 1999). Finally, the potential natural vegetation (biome) of the areas affected by expansion is determined by identifying these areas on a digital biome map with a global overview of 15 potential natural vegetation types (Ramankutty and Foley 1999). This full procedure is described by Kløverpris (2008).

3 Results

The studied increase in household wheat consumption leads to an increase in the global production of wheat distributed among the marginal wheat suppliers, i.e. those responding to a change in demand. The changes in wheat production affect the production of other crops and livestock due to the displacement–replacement mechanisms (Kløverpris et al. 2008). All the changes in agricultural production result in net expansion of the global agricultural area, which affects natural areas in terms of biomes. This section presents changes in agricultural production as well as the resulting land use effects. The results are explained and interpreted in terms of the assumptions of the GTAP model and the economic theory behind it.

[3] Determined from the overlay mentioned in Section 2.1.

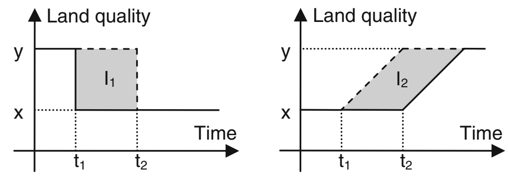

Fig. 3 Impact of accelerated transformation (I_1) and delayed relaxation (I_2). The *full line* indicates land quality at the studied increase in crop demand, and the *dashed line* indicates the development if the current trend in demand is unaffected (dynamic reference situation). I_1 is equal to I_2

A key purpose of LCA is to determine the environmental consequences of product consumption. All results are therefore presented per tonne of increased wheat consumption in the households of the scenario countries. Note that the increase in consumption is slightly lower (by less than 0.2%) than the demand shock (500,000 tonnes). This is the net effect of two opposing forces, an increase by the demand shock itself (500,000 tonnes) and a small decline due to a higher wheat price generated by the demand shock (a negative relationship between demand and price is a standard assumption in economics).

3.1 Localisation of affected wheat suppliers and characterisation of increased wheat production

Figure 4 shows the estimated changes in wheat production induced by wheat consumption. The results include the wheat seeds consumed by the wheat sector itself. That is why the total increase in wheat production in the Chinese scenario exceeds 1 tonne. In the Brazilian, Chinese, Danish and US scenario, the net increase in total wheat production (subtracting the wheat sectors' own consumption) is, respectively, 84%, 98%, 91%, and 93% of the increased household wheat consumption in the scenario country (calculated based on background data not available in this paper). This shows that when wheat is consumed, most of it is provided by increased production but some of it (2–16%) is taken from applications in other sectors because the supply of wheat is not perfectly elastic.

The results in Fig. 4 reflect existing trade patterns as well as the prevailing constraints on land availability. Increased wheat consumption in China and Brazil is almost entirely sourced from domestic production. Prior to the change in demand, imports account for, respectively, 1% and 3% of the two countries' household wheat consumption. An increase in wheat demand is therefore met primarily by an increase in domestic wheat production. In contrast, 40% of US and 23% of Danish household wheat consumption is covered by imports (prior to the change in demand), and substantial parts of the increased demand for wheat is consequently met by growth in wheat production outside these countries.

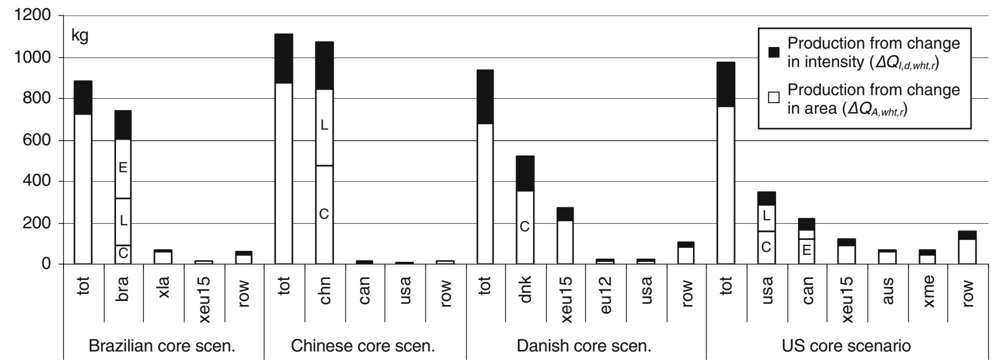

Fig. 4 Wheat production caused by consumption of one (additional) tonne of wheat in the four core scenarios. For the scenario countries, the change in wheat area is split into expansion (*E*) and displacement of other crops (*C*) and livestock (*L*). For Canada in the US scenario, production caused by expansion is also indicated. The regions with the lowest increase in wheat production are presented together as '*row*' (rest of the world), and '*tot*' stands for total

Similarly, which countries respond to the increasing demand for wheat imports is largely determined by existing trade patterns. For instance, higher household wheat consumption in the USA results in a significant increase in Canadian wheat production due to the traditional close trade relations between the two countries. This trade pattern in turn reflects low costs of transportation and the relatively small barriers to trade within the North American free trade area.

Interestingly, the availability of unused agricultural land has little influence on *where* the extra wheat is produced. The reason is that the production costs related to land typically constitutes 20% or far less of the total production costs of crops. Therefore, a change in land prices has a minor effect on market prices (which depend on production costs). On the other hand, land availability determines *how* the extra wheat is produced in the regions responding to the change in demand. In countries such as Brazil and Canada with large areas of unutilised cultivable land, expansion accounts for a large share of the increased crop production. For instance, one third of Brazil's increase in wheat production derives from expansion. Denmark and China utilise all of their cultivable land, and their increase in wheat production consequently derives from displacement and intensification. The reason why wheat production does not displace livestock in Denmark is that pastures are insignificant on Danish cultivable land.

In the Brazilian core scenario, the intensified wheat production in Brazil corresponds to an increase in wheat yields of 1.8% (37 kg/ha). Compared to the rather low initial wheat yields calculated for Brazil (roughly 2 tonnes/ha or less than a third of Danish wheat yields), the calculated yield increase per hectare seems realistic. In the Chinese and the US core scenarios, the intensified wheat production in the scenario country corresponds to an increase in wheat yields of, respectively, 0.12% (5 kg/ha) and 0.06% (1 kg/ha), which is also considered realistic. In the Danish scenario, however, the number is 1.7% or 120 kg/ha, which is quite high considering the strict regulations on pesticides and fertilisers in Denmark and the fact that Denmark already has some of the world's highest wheat yields. If the restrictions mentioned had been included in the modelling, the intensification in Denmark (and probably the rest of EU) would most likely have been somewhat lower.

3.2 Production changes for non-wheat crops and livestock

The increased production of wheat leads to changes (mainly reductions) in the areas planted with other crops. However, this is partly compensated for by intensification. The changes in production of non-wheat crops (the remaining seven crop sectors) are added up to get an indication of the ratio between reduced production due to change in area and the production from change in intensity (Fig. 5).

For the scenario countries, there is a direct connection between the wheat production obtained by displacement of other crops (see Fig. 4) and the reduced production of other crops due to change in area (see Fig. 5). The reason for the large reduction in non-wheat crop production in the Brazilian core scenario (compared to the relatively small increase in Brazilian wheat production caused by crop displacement) is that most of the crop sectors in Brazil have a significantly higher yield per hectare than the wheat sector.

Figure 5 displays a large variation in the degree to which displacement of non-wheat crops is compensated for by intensification of production. In Brazil and China, the intensification of non-wheat crop production almost set off the reduction in production caused by displacement with wheat (with yields of non-wheat crops increasing by roughly 0.04% and 0.035%, respectively). In contrast, intensification generates less than half the quantity of displaced crops in Denmark and the USA (where the yields of non-wheat crops rise by roughly 0.6% and 0.01%, respectively). This is not

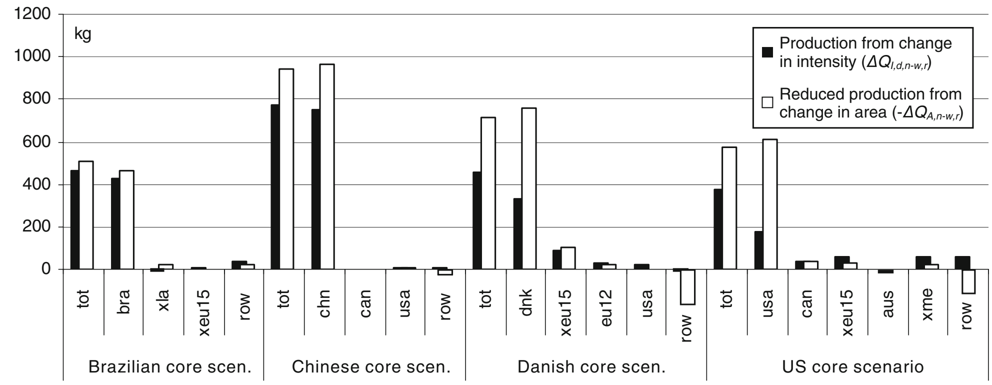

Fig. 5 Production of non-wheat crops (*n-w*) caused by consumption of one (additional) tonne of wheat in the scenario countries. Note that the *white bars* indicate *reduced* production so the net change in production is the difference between the *black bars* and the *white bars*. The regions not mentioned explicitly are presented together as '*row*' (rest of the world), and '*tot*' stands for total

explained by differences in ability to intensify production but rather by the existing trade patterns. The economies seek to compensate for reduced cultivation of non-wheat crops due to displacement in the cheapest way possible. In Denmark and particularly the USA, international trade costs are relatively low, and it is cheaper to reduce exports and/or raise imports of crops than to intensify production. In a sense, these countries succeed in 'exporting' much of the displacement, thus sharing the burden of intensifying production over a wider area. This also accounts for the 'negative displacement' observed in some of the columns for the rest of the world (row) in Fig. 5; the rising demand from the scenario countries induces an expansion in the area for cultivation of non-wheat crops. In contrast, Brazil and China do not trade much in agricultural commodities (although they do have considerable international trade in processed food), and there are fewer opportunities to obtain displaced production through trade. Hence, they find it less costly to intensify production. Note that at the global scale, the degree of compensation is still lower in the Danish and US scenarios, implying a greater reduction in the final consumption of other crops compared to the Brazilian and Chinese scenarios. Again, the costs of adjustment, this time in terms of reduced consumption, are spread over a wider area, reducing the need for intensification.

Despite the displacement of livestock (see Fig. 4), the global production in the two affected sectors (ctl and rmk) does not change significantly (calculation based on Eq. 14 in ESM). The reason is that the decrease in cultivable land in the livestock sectors is partly set off by expansion on grazable land (see Fig. 6) and partly by substitution with capital and labour. As these two production factors are not normally accounted for in LCA, livestock production has been omitted in the remaining part of the paper except for its influence on net expansion.

3.3 Net expansion induced by wheat consumption

The changes in area in the different crop and livestock sectors add up to a net change in the use of cultivable and grazable land. Figure 6 shows that increased wheat consumption in Denmark and the USA leads to considerable expansion elsewhere in the world, whereas increased consumption in Brazil primarily leads to domestic expansion. Increased wheat demand in China primarily leads to intensification and expansion effects are limited. More than 90% of the net expansion takes place in the same eight regions and more than two thirds (and up to 87%) of the total net expansion occurs on cultivable land.

The large differences in total net expansion observed between the four core scenarios are caused by several factors. In the case of China (which has no expansion potential), intensification compensates for a large fraction of the displacement of non-wheat crops (see Fig. 5). This means that little production (and thereby expansion) is necessary outside the country. The differences in global net expansion between the remaining three scenarios have to do

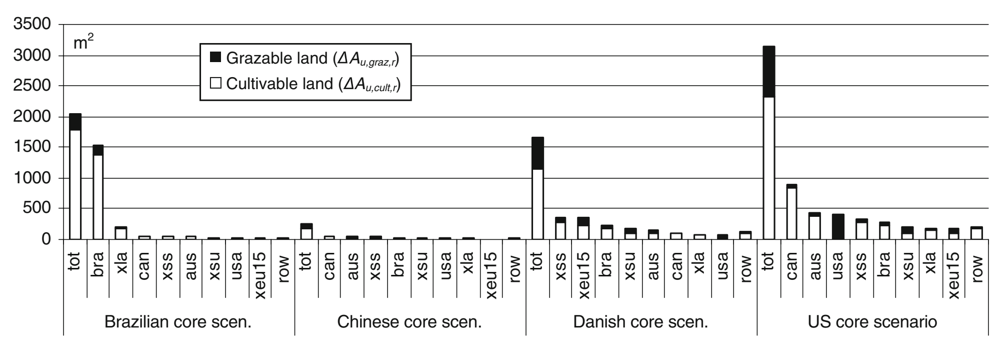

Fig. 6 Net expansion caused by consumption of one (additional) tonne of wheat in the scenario countries. The regions with the lowest net expansion are presented together as '*row*' (rest of the world), and '*tot*' stands for total

with several factors including yields per hectare in the regions where expansion takes place. The lower the yields, the more land is necessary for the increase in production caused by an overall change in the agricultural area. Of course, expansion is also influenced by the level of intensification in the main regions affected.

The expansion on grazable land (13–31% of global net expansion) takes place because of livestock displacement on cultivable land. To compensate for this loss of land in the livestock sectors, grazable land is taken into production. Thereby, wheat consumption pushes livestock from one land type to another.

The reason why 75% of the expansion in the Brazilian scenario takes place in Brazil itself is the country's large expansion potential previously mentioned. Ten per cent of the expansion takes place in the rest of South America (excluding Peru) due to easy market access and availability of land (respectively, 82% and 84% utilisation of cultivable and grazable land).

The expansion in the Danish, Chinese and US scenario is distributed over several countries. This shows how the displacement–replacement mechanisms channel the land use effects in terms of expansion through the agricultural system. The reason why the distribution of expansion between the affected countries is not the same in each scenario has to do with several factors, e.g. trade barriers, transport costs and the Armington elasticities. All expansion in the USA occurs on grazable land because of the full utilisation of cultivable land.

3.4 Land use LCI for wheat consumption

By use of the method summarised in Section 2.4, the results in Fig. 6 are converted to a land use life cycle inventory (LCI), which lists the biomes expected to be affected by the expansion induced by consumption of 1 tonne of wheat (Table 3). In the Brazilian scenario, almost 75% of the expansion takes place on tropical evergreen forest mainly in Brazil itself (and a small fraction in xla and xss). In the Chinese scenario, savanna and boreal deciduous forest each make up roughly 20% of the biomes affected, whilst open shrubland and tropical evergreen forest accounts for roughly 15% each. Interestingly, this distribution is more or less the same in the US scenario except that boreal deciduous forest accounts for 27% of the biomes affected. This difference is explained by Canada's large share of global expansion in the US scenario (see Fig. 6). Besides that, the regions contributing to global net expansion in the US and the Chinese scenarios appear in the same descending order if the USA is ignored (see Fig. 6). This also explains the similarities in distribution of biomes affected in the two scenarios. In the Danish scenario, savanna and tropical evergreen forest dominates the biomes affected by, respectively, 18% and 21%, whilst dense shrubland account for 15%. The tropical forest is mainly located in Sub-Saharan Africa and Brazil (more or less equal shares) and the savanna is mainly located in Sub-Saharan Africa and Australia. The figures in Table 3 can be used as the basis for a life cycle impact assessment of the land transformation and subsequent occupation induced by wheat consumption (see Fig. 3).

4 Sensitivity analyses

Some aspects of the economic modelling could have been performed differently. This section investigates the sensitivity to changes in the modelling considered relevant for the methodological exploration of life cycle inventory modelling of land use.

4.1 Linearity check

The global economic system is not linear. In the double demand (DD) scenarios, it is therefore tested how it will affect the results when the change in wheat demand is one million tonnes instead of 500,000. This only has a minor influence on global production of wheat and other crops (given per tonne of household wheat consumption in the scenario countries). The largest differences are observed in the Brazilian DD scenario where the global net expansion is 3% lower compared to the core scenario. The results of the core scenarios can therefore be considered valid for LCAs addressing changes in wheat consumption below one million tonnes per year. Figure 7 shows how the results for net expansion in the Danish DD scenario are practically unchanged compared to the core scenario (see Fig. 6).

Table 3 Land use LCI for consumption of 1 tonne of wheat in the core scenarios

Biomes (m^2)	Braz.	Chin.	Dan.	US
Savanna	230	53	300	590
Tropical evergreen forest	1,500	44	350	460
Boreal deciduous forest	57	49	97	850
Evergr./deciduous mixed forest	25	14	200	160
Dense shrubland	29	10	260	140
Grassland/steppe	120	24	150	210
Open shrubland	43	38	170	480
Boreal evergreen forest	4	4	10	51
Rest (biomes unknown)	35	24	130	210
Total net expansion	2,000	260	1,700	3,200

Numbers indicate the areas subject to expansion (accelerated transformation or delayed relaxation) including 1 year of agricultural occupation. Biome definitions adopted from Ramankutty and Foley (1999). Inconsistencies occur due to rounding

4.2 Demand driven technological development

Technological development can help farmers to obtain higher crop yields per hectare (intensification) without changing the basic inputs to crop production. To investigate the effects of demand-driven technological development on global net expansion, the technological development (TD) scenarios are constructed. This is done by linking price of cultivable land with the productivity of cultivable land in the GTAP model, so a 2% increase in land price automatically causes a 1% increase in land productivity. More specifically, 100 ha of land with productivity improved by 1% are equivalent to 101 ha of land with unimproved productivity. The magnitude of the relationship between land price and land productivity is arbitrarily chosen as no data are identified to form an empirical basis. The relationship is asymmetric in the sense that a decrease in land price will not lead to a decrease in land productivity. This is to reflect the fact that technological development is not rolled back in case of decreasing demand. The mechanism described is only implemented for the crop sectors.

In the TD scenarios, the total increase in wheat production is only slightly different than in the core scenarios (4% higher in the Danish scenario, less than 1% change in the others), but as expected, intensification accounts for a larger share. This is more pronounced in the Danish and US TD scenarios than in the Brazilian and Chinese TD scenarios. In all the TD scenarios, the displacement of non-wheat crops is significantly higher than in the core scenarios, but this is almost fully compensated for by intensification (99%), except for the Chinese scenario in which the compensation level is 88%. Compared to the core scenarios, the established link between land price and land productivity reduces the net expansion in the TD scenarios, but not with the same share. In the Danish and Chinese TD scenarios, the global net expansion is reduced with roughly 80%, whereas it is, respectively, 57% and 27% in the in the US and Brazilian TD scenarios. Figure 7 shows the results for net expansion in the Danish TD scenario.

4.3 Armington elasticities

As mentioned previously, the Armington elasticities (representing the inertia of global trade patterns) tend to increase with the time perspective. In this sensitivity analysis, the effects of increasing the Armington elasticities applied in the core scenarios are investigated. The elasticities are doubled in the double Armington (DA) scenarios (four times the standard Armington elasticities) and then doubled again in the quadruple Armington (QA) scenarios (eight times the standard values).

Higher Armington elasticities imply that consumers are more inclined to substitute cheaper imports for more expensive domestic production. In other words, with less inertia in the global trade, the international trade patterns play a less dominant role (compared to, say, the potential for expansion in the agricultural area) in explaining the results. Imports of wheat in the scenario countries increase more, causing their own increase in wheat production to go down compared to the core scenarios. The domestic production increase in the scenario countries is 20% and 40% lower in all the DA and QA scenarios, respectively, except for the Chinese DA and QA scenarios in which the increase is, respectively, 4% and 10% lower.

Compared to the core scenarios, the overall increase in wheat production is lower in the DA and QA scenarios, but more wheat is produced outside the scenario countries. The effect on global net expansion depends on how the scenario country and its suppliers increase wheat production. When the increase in wheat production partially moves out of Brazil due to the higher Armington elasticities, the global net expansion is lower than in the core scenario (DA, −13%; QA, −24%). This is because expansion plays a significant role in Brazil's domestic increase in wheat production (see Fig. 4). On the other hand, increasing Armington elasticities lead to increased global net expansion from wheat consumption in China (DA, 55%; QA, 124%) and Denmark (DA, 30%; QA, 50%). This is because wheat production is partially moved to regions with expansion potential. For US wheat consumption, the changes in Armington elasticities do not change the global net expansion significantly, although there is also some redistribution of expansion between regions. Figure 7 shows the results for net expansion in the Danish DA and QA scenarios. In summary, the results of the modelling are clearly sensitive to modifications of the Armington elasticities. Interestingly, the fraction of increased global wheat production achieved through intensification is more or less unaffected by the Armington modification.

5 Uncertainties

This section provides a qualitative assessment of the most important sources of uncertainty influencing the results of the study.

The land supply curves introduced in the modified GTAP model are based on data and assumptions concerning land availability and land utilisation. The data on areas not available for agriculture (steep and protected areas, human settlements and deserts) are considered to be of good quality, but lack of information about possible overlaps between these areas creates inherent uncertainties in the general procedures applied to calculate the areas of

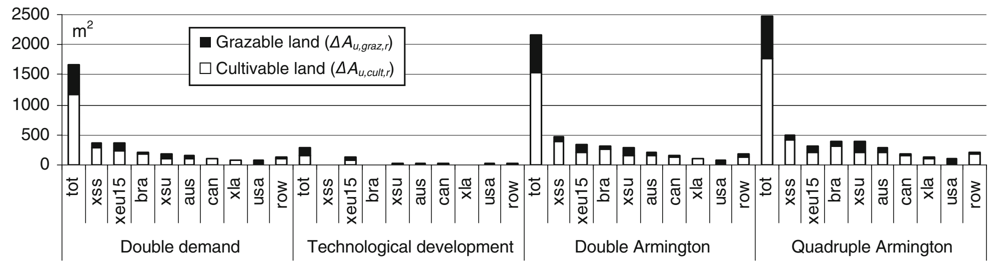

Fig. 7 Sensitivity analysis of the net expansion caused by consumption of one (additional) tonne of wheat in Denmark. The regions with the lowest net expansion are presented together as '*row*' (rest of the world), and '*tot*' stands for total

cultivable and grazable land available for agriculture (for details, see Baltzer and Kløverpris 2008). Furthermore, the assumption that arid, semi-arid and dry sub-humid areas can be used as pastures (see Section 2.1) may cause an overestimation of expansion on grazable land (see Fig. 6). As this only constitutes a minor part of global net expansion, the uncertainty introduced is judged to be low.

To ensure consistency in the modelling, data from around 2001 have been used to the extent possible. The GTAP database corresponds to 2001; data on cropland and pasture areas are from around 2000 (see Section 2.1), and data on crop production and area harvested are from 2001 (see ESM). The uncertainty introduced by assuming results to be valid for current conditions is considered to be low especially because of the update of the GTAP database (see Section 2.1).

The calculation of the areas occupied by the different crop sectors (Eq. 3 in ESM) is based on yearly areas harvested, which may be larger than actual cropland areas because some crops are harvested more than once a year (high cropping intensity). However, crop sectors in the same region are likely to have similar cropping intensities because of similar climatic conditions. This reduces the uncertainty introduced in the procedure described.

The areas calculated in Eq. 3 in ESM are combined with crop production data in Eq. 5 (see ESM) to calculate yearly crop yields per hectare. This combination of datasets deriving from two different sources also introduces some uncertainty, which is difficult to assess as no comparable global dataset is identified. However, the uncertainties relating to Eqs. 3 and 5 in ESM only affect the *distribution* between crop production from, respectively, change in area and intensity. The total crop production in a sector is unaffected as it is calculated from the GTAP output and the initial crop production (appears implicitly from Eq. 7 in ESM).

The identification of biomes affected by expansion is partly based on a qualitative assessment. However, the conclusions on the trends in utilisation of cultivable and grazable land are fairly unambiguous for the eight regions studied, and the certainty of this part is generally considered good. The subsequent identification of the areas affected within the regions (and thereby the biomes affected by expansion) is less certain (Kløverpris 2009a). Consequently, the result should only be considered a reasonable estimate of the biomes most likely to be affected by agricultural expansion.

6 Discussion

The method presented in the present paper makes it possible to produce even more detailed results than those presented in Section 3. Furthermore, the method contains elements with general implications for LCA. These aspects are discussed below.

6.1 Possibilities for a more detailed and disaggregated land use LCI

Some simplifying assumptions regarding land quality are used in this study (see Section 2.4). Only net expansion of the agricultural area is considered, and thereby the land use LCI (see Table 3) does not distinguish between transformation from nature to cropland and transformation from nature to pastures (although the two agricultural land uses may result in different land qualities). If such a distinction were made, it would be necessary to list the land converted from pastures to cropland (displacement of livestock) in the land use LCI. The background data of the study actually offer this possibility (see Kløverpris 2009b). In fact, it would be possible to include all shifts in land use between the eight crop sectors, the two land-dependent livestock sectors and nature in all of the 22 GTAP regions. Furthermore, it would be possible to distinguish between the two types of net expansion (accelerated transformation and delayed relaxation). This level of detail is considered exaggerated in the present paper, but is nonetheless obtainable with the method described.

6.2 The influence of existing trade patterns

It may seem strange that the existing trade patterns have such a large influence on the suppliers responding to increased wheat demand whilst the availability of unused land only plays a minor role. The reason is that trade patterns are governed by prices of different suppliers (taking into account transport, tariffs and other trade

barriers). If Denmark satisfies most of its current wheat demand from domestic production and imports from the rest of the EU, it must be because they are the cheapest suppliers under the current market conditions. As mentioned in Section 3, the price of land only has little influence on the price of crops. Therefore, the change in demand for wheat will not lead to a significant change in crop prices, and trade patterns are only affected marginally. Fair to say, there is one more significant aspect explaining why existing trade patterns have such a large influence on the results, namely the Armington elasticities.

6.3 Armington elasticities and time perspectives in LCA

The inertia of global trade patterns represented by the Armington elasticities is normally not considered in LCA. However, this aspect should be acknowledged whilst still respecting the long-term perspective applied in LCA. That is why Armington elasticities twice as high as the standard values are applied in the core scenarios. It may be argued that a further enlargement of the Armington elasticities would be more in line with the LCA methodology, but considering the land use LCIA framework mentioned in Section 2.4 in which a change in land quality is compared to a reference situation (business as usual), it does not make sense to apply a time perspective which is too long. The reason is that land use change induced by crop consumption occurs within a foreseeable future, i.e. when the market reacts. This reaction takes place under the given constraints represented by the Armington elasticities. Thereby, the elasticities are legitimate in an LCI analysis. If economic modelling gains a footing in LCA, it would be desirable to obtain consensus on the appropriate size of the Armington elasticities.

6.4 LCI data based on consumption instead of production

Most LCI data currently available represent *production* of a certain amount of product. The land use LCI presented in Table 3 is different as it represents *consumption* of a certain amount of product. As described in Section 3.1, increased household consumption of 1 tonne of wheat causes the net production of wheat to increase by 840–980 kg whilst the total production of other crops decreases by 41–260 kg. All changes in agricultural production are triggered by wheat consumption, and it is the land use consequences of this consumption, which are reflected in Table 3. The reason why the net production of wheat does not increase with 1 tonne (equivalent to the increase in household consumption) is that the wheat sector has to compete with other sectors for resources in terms of intermediate inputs and primary production factors being capital, labour and land. The amount of capital and labour at a given moment is fixed so land is the only primary production factor for which the amount can be increased. As more land is being utilised, the land price increases (see Fig. 2). The marginal costs of crop production thereby increase, which explains why the supply of crops is not perfectly elastic. In order to determine the environmental impacts of crop consumption, this premise of the market should be taken into account as it is done in this study.

6.5 Accounting for the decrease in demand for non-wheat products

The competition for resources is not the only reason for the decrease in production of non-wheat crops. As described in Section 2.2, the increased demand for wheat is simulated at the expense of demand for other products due to the budget constraint of the households. Because this decrease in demand is distributed over many other products, the influence on the non-wheat crops is relatively small. Nonetheless, it affects the results to some degree. This situation is not uncommon in LCA where one alternative is typically studied in comparison to another. In other words, LCA is applied to study the consequences of increasing the demand for one solution and simultaneously decreasing the demand for another solution. The problem is that when constructing inventory data, only one side of the story is considered, namely the increase in demand. Not until the full LCA is performed is the decrease in demand addressed. However, if life cycle inventory data were established by use of a general economic equilibrium model and the decrease in demand were always modelled consistently (e.g. by the procedure described in Section 2.2), the decrease in demand implicitly reflected in the obtained LCI data would tend to be cancelled out once a full LCA were performed. This opens up new perspectives and possibilities for the future construction of life cycle inventories.

7 Conclusions

The analysis in the present paper shows that economic modelling in combination with geographical data and agricultural statistics can indeed help to overcome some of the obstacles of identifying ultimate or marginal land use changes when studying crop consumption in LCA. It is shown that the displacement–replacement mechanisms of agricultural land use can be handled in a global context, and the relevance of where the demand is increased can be taken into account (the geographical dependency). Furthermore, the methodology eliminates the long-known problem of allocating initial transformation impacts to subsequent land use activities, and it provides an estimation of the ratio

between production achieved through change in, respectively, intensity and area. The linearity check in the sensitivity analyses shows that the results are valid for changes in wheat consumption within an amount of one million tonnes per year, which means that the results are applicable to a wide range of LCAs. Furthermore, the study presents a proposal on how to model the influence of demand on technological development, but the exact relationship is not determined. The results are sensitive to changes in the Armington elasticities in the GTAP model representing the inertia of global trade patterns. In this study, it is considered reasonable to double the standard Armington elasticities.

In the core scenarios, it is estimated that the consumption of 1 tonne of wheat in, respectively, Brazil, China, Denmark and the USA leads to a global increase in wheat production between 880 kg (Brazil) and 1,100 kg (China). The net increase in wheat production (excluding the wheat used for seeds) is between 840 kg (Brazil) and 980 kg (China). Brazil and China account for most of the global increase in wheat production themselves (84% and 97%, respectively), whilst Denmark and the USA account for roughly half and one third, respectively.

In the core scenarios, intensification accounts for approximately 20% of the global increase in wheat production, except for the Danish scenario in which it is almost 30%. This may be overestimated as restrictions on fertilisers in Denmark (and the EU) are not taken into account.

In Brazil, roughly half of the increase in wheat production from change in wheat area comes from expansion. The rest comes from displacement of other crops and livestock. In China and the USA, the increase in wheat production from change in the wheat area comes from displacement of other crops and livestock, and in Denmark, it only comes from displacement of other crops (as livestock is insignificant on cultivable land). Despite livestock displacement, there is no significant change in the overall livestock production partly because production is moved to another land type (grazable land) and partly due to substitution of land with capital and labour.

In Brazil and China, the displacement of other crops is almost fully compensated for by intensification (92% and 78%, respectively), whilst Denmark and the USA mainly compensate the displacement of other crops by increased imports (but also some intensification).

Consumption of wheat in China and the USA is expected to mainly affect savanna, boreal deciduous forest, open shrubland and tropical evergreen forest. However, the global net expansion induced by consumption of 1 tonne of wheat in China is estimated at 260 m^2, whereas it is roughly 3,200 m^2 for 1 tonne of wheat consumed in the USA. For Brazil, the net expansion per tonne of wheat consumed is approximately 2,000 m^2 presumed to mainly affect tropical evergreen forest in the country itself, and for Denmark, it is roughly 1,700 m^2 presumed to mainly affect savanna, tropical evergreen forest and dense shrubland.

8 Recommendations and perspectives

As mentioned previously, integration of mechanisms simulating fertiliser and pesticide restrictions in the GTAP model would raise the quality of the results. The assessment of the amount of grazable land can also be improved. Taking irrigation into account would also improve the modelling as well as a further differentiation between different levels of land fertility. Finally, the method could be expanded to include not just land use (transformation and occupation) but also the intensification aspects and the implications for life cycle inventory modelling. This has briefly been discussed in the first paper of this series (Kløverpris et al. 2008).

The method applied in this study to identify land use induced by crop consumption could inspire a new way of doing LCA, taking its point of departure in consumption and not production. If this is based on economic modelling, it is recommended to seek consensus on how to handle the Armington issue.

The method may also inspire the debate about biofuels and the natural areas affected by their production. However, it is important to keep in mind that the examples presented in this study consider marginal changes in crop consumption compared to the total market, whereas the production of biofuels typically concern larger changes. Furthermore, it would be necessary to construct a much more specific demand change in the case of biofuels, taking into account the interaction with fossil fuels.

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